



Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)

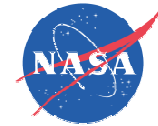
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3rd NASA GRC Propulsion Control and Diagnostics Workshop
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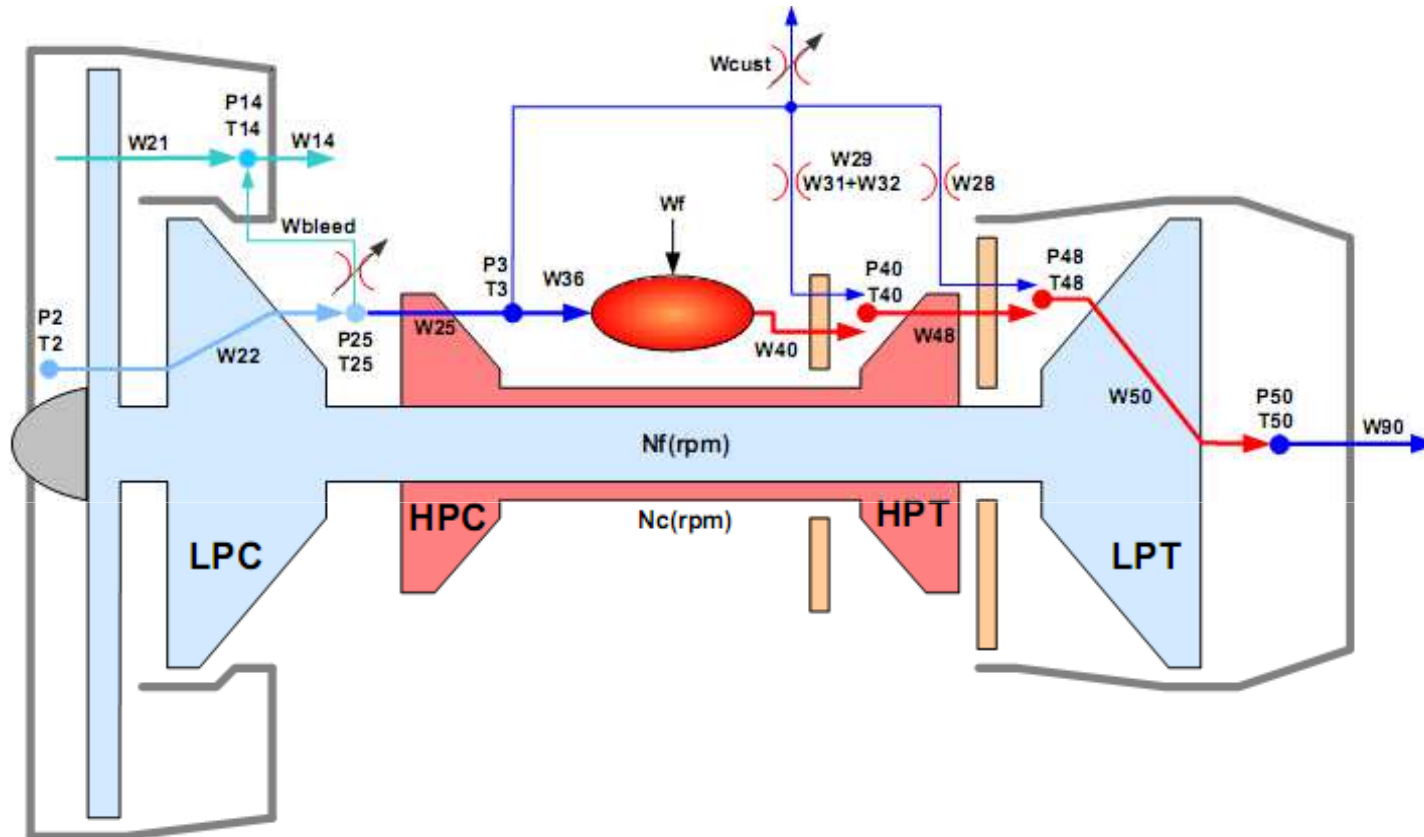


C-MAPSS40k Overview

- Engine description
- Engine simulation
- Control system
- User features
- Recent updates & ongoing work



Engine Description

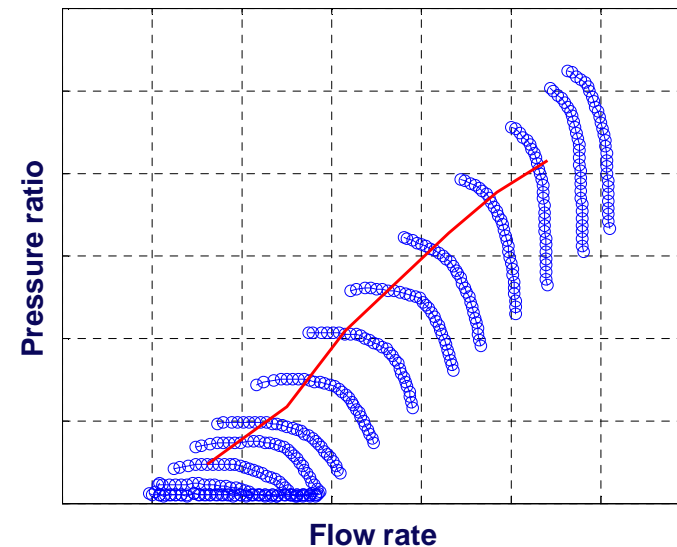
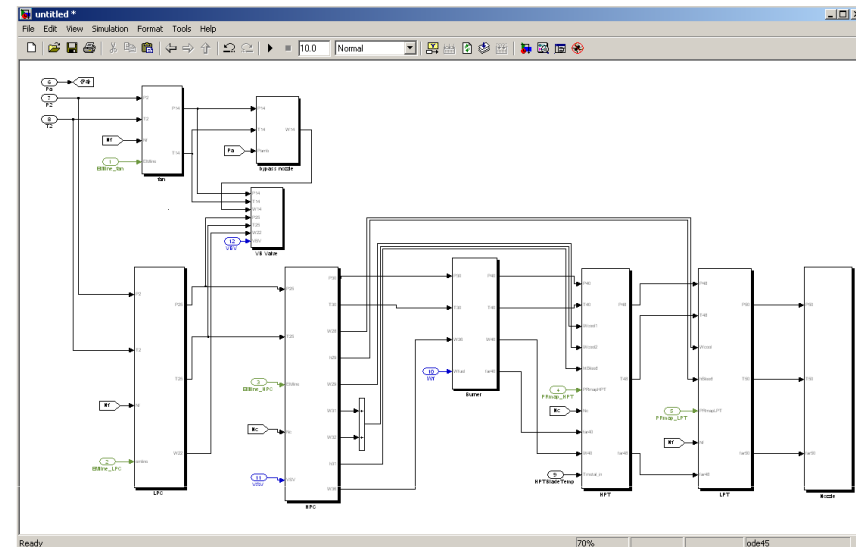


- 40,000-lb_f thrust class
- High-bypass, dual-spool turbofan



Engine Simulation

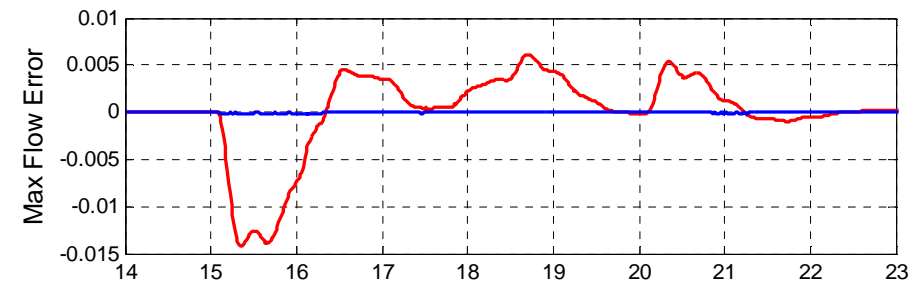
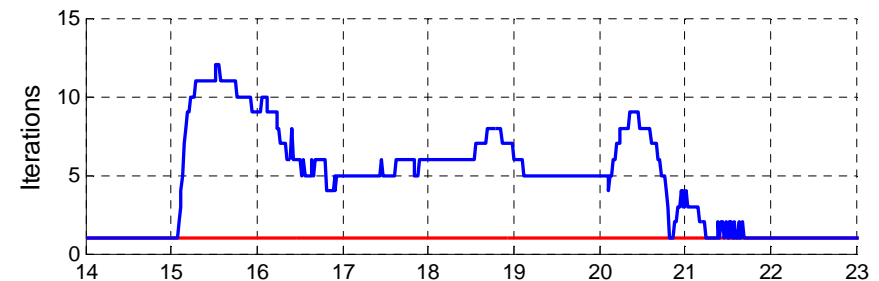
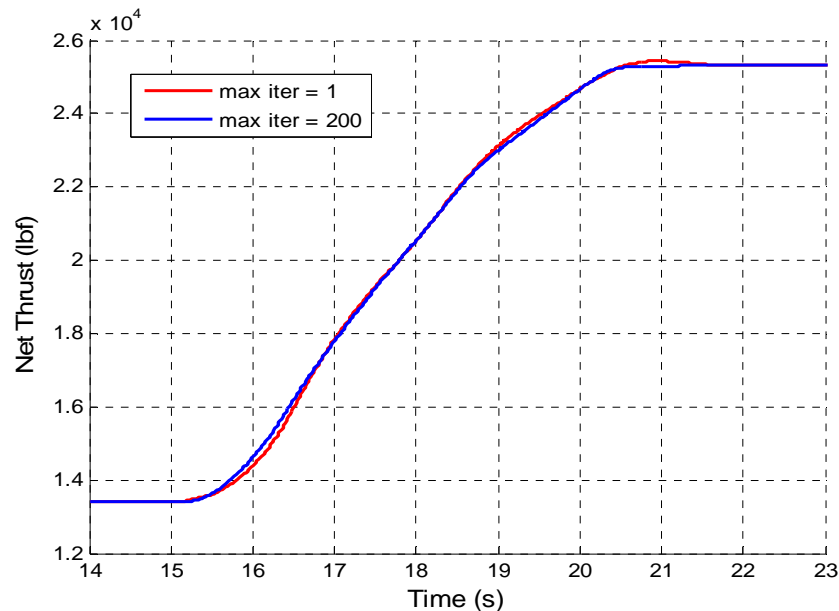
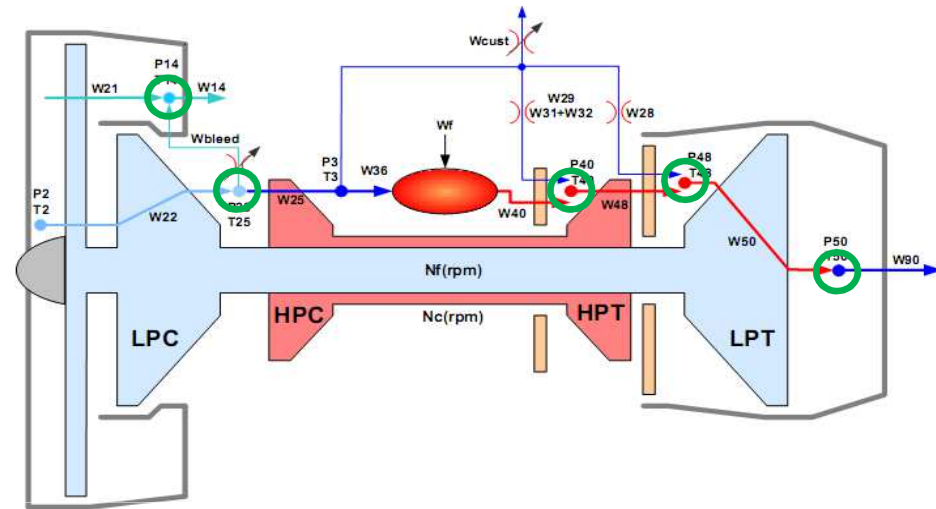
- Component-level modeling
- Physics-based
 - Aerothermodynamics
 - Performance maps
- Operates over wide range of environmental conditions
 - Mach, altitude, DTamb
- Faster than real-time
 - Components coded in C
 - Assembled in Simulink
 - Run via MATLAB
- Detailed stall margin model
- Engine health condition





Engine Simulation

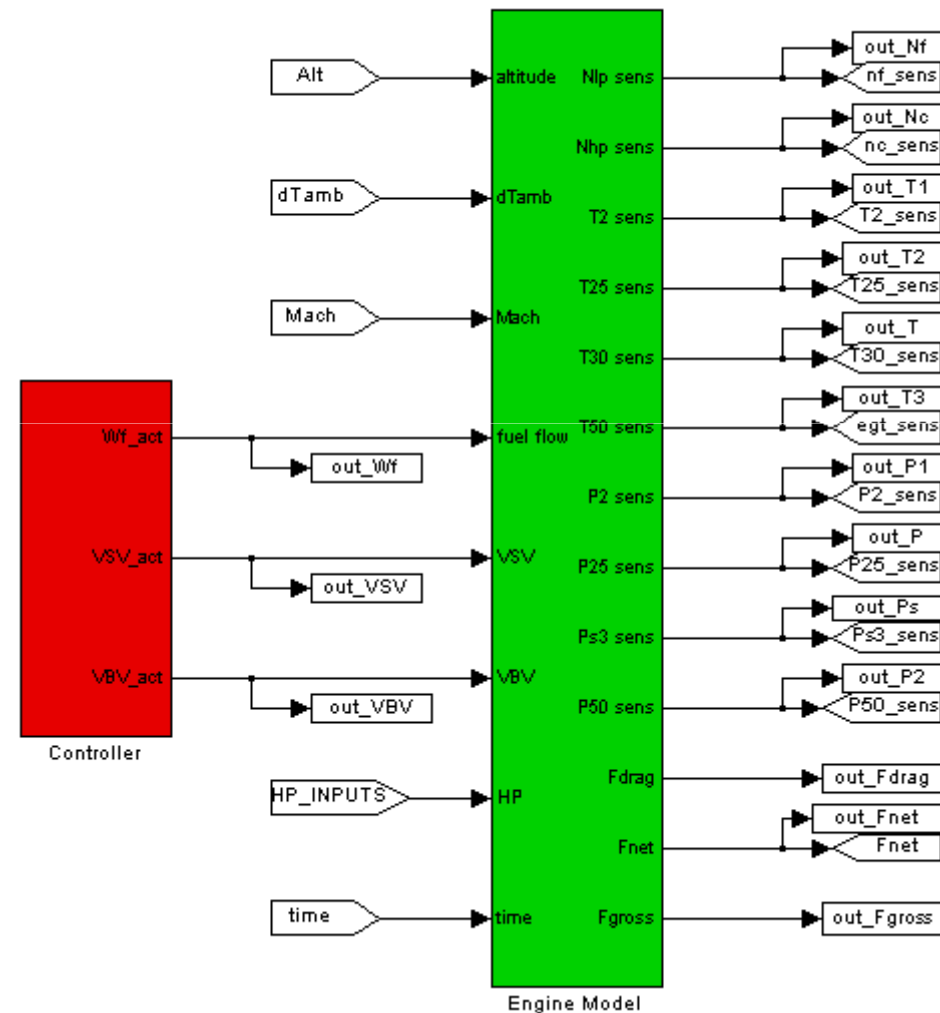
- Dynamics
 - Nonlinear dynamical system with spool speeds as state variables
- Flow continuity
 - Iterate to ensure mass flow balance at each time step
 - Realistic transient performance





Control System

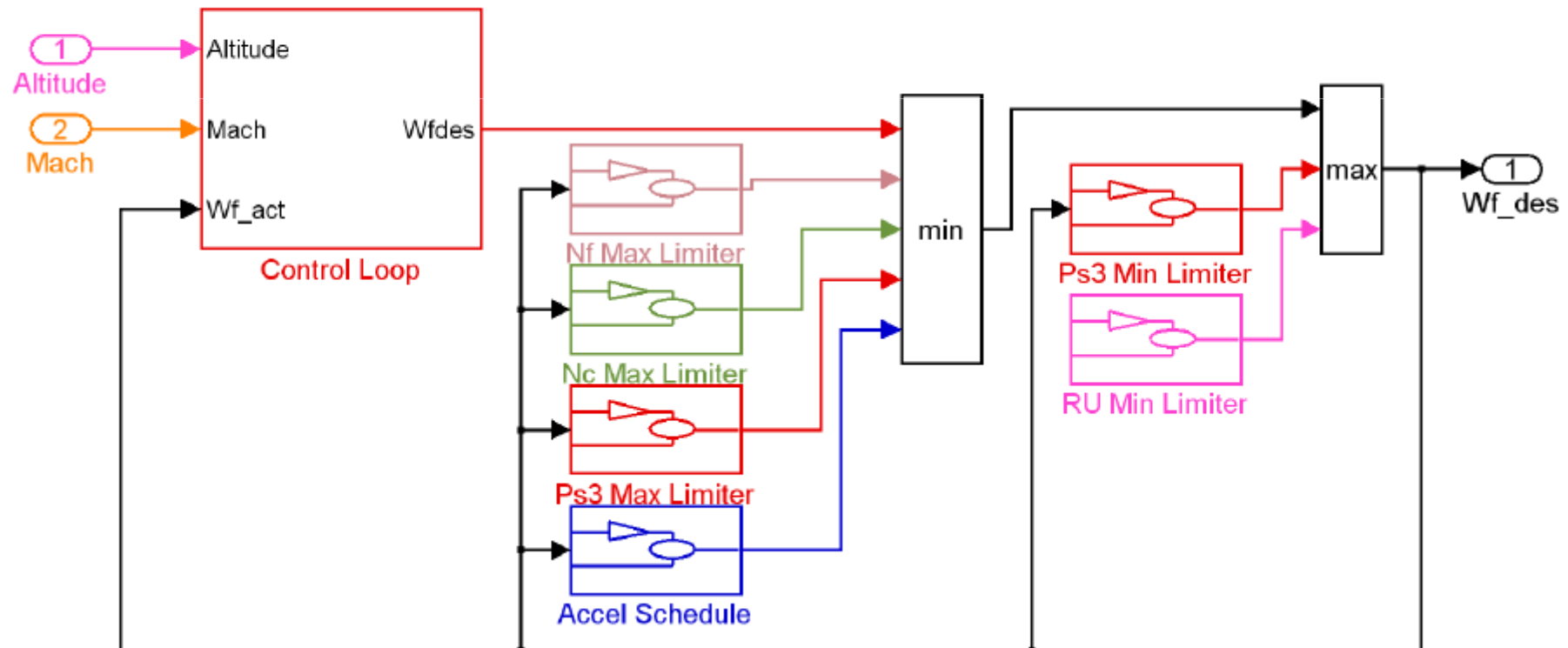
- Representative of industry standard
- Controls engine based on throttle input
- Calculate fuel flow, variable stator vane position (VSV), variable bleed valve position (VBV)
- Uses typically sensed engine outputs
- Simulates actuator/sensor dynamics





Control System

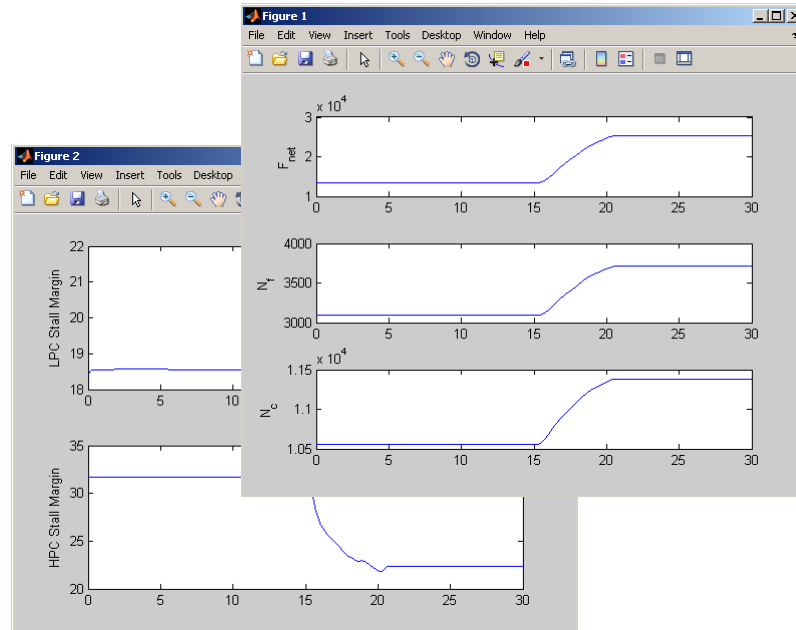
- VSV, VBV are scheduled on sensed engine parameters
- Fuel: gain-scheduled PI feedback control on EPR/Nf with protection logic





User Features: Graphical Interface

- Environmental & throttle inputs
- Control settings
- Simulation settings
- Engine health settings
- Plot & save data



C-MAPSS40k Interface

C-MAPSS40k Graphical Interface

Time-Varying Inputs

Time Vector: [0 15 20 30]

Altitude: 4000

Mach Number: 0.1

dTamb: 0

PLA: [55 55 60 60]

Sim Duration: 30 sec

Engine Health Parameters

Engine Deterioration: 0.0

HP Time Vector: [0 15 20 30]

Fan Eff: [0.0]

Fan Flow: [0.0]

Fan PR: [0.0]

LPC Eff: [0.0]

LPC Flow: [0.0]

LPC PR: [0.0]

HPC Eff: [0.0]

HPC Flow: [0.0]

HPC PR: [0.0]

HPT Eff: [0.0]

HPT Flow: [0.0]

LPT Eff: [0.0]

LPT Flow: [0.0]

Engine Controller

Control Mode:

Engine Limiters:

Operational State

Power Takeoff: 0 HP

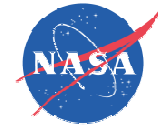
Customer Bleed: 0 psi

Solver Configuration

Error tolerance: 0.001 lbm/sec

Max iterations: 200

Ts: 0.015 sec



User Features: Script/Command Line

- MATLAB command line
- MATLAB scripts
- MS Excel input profile generation

	A	B	C	D	E	F
1	C-MAPSS40k Input Flight Profile					
2						
3	Environmental Inputs					
4	Time Vector (sec)	0	10	15	135	137
5	Altitude (ft)	971	971	971	6000	6000
6	Mach Number	0	0	0.15	0.4	0.4
7	dTamb (deg F)	0	0	0	0	0
8	PLA (deg)	40	40	78	78	73

The image shows the MATLAB R2011b interface. The Command Window displays the output of running a script, indicating that the C-MAPSS40k model is ready to execute. The Editor window shows the script file `define_inputs.m` with the following code:

```

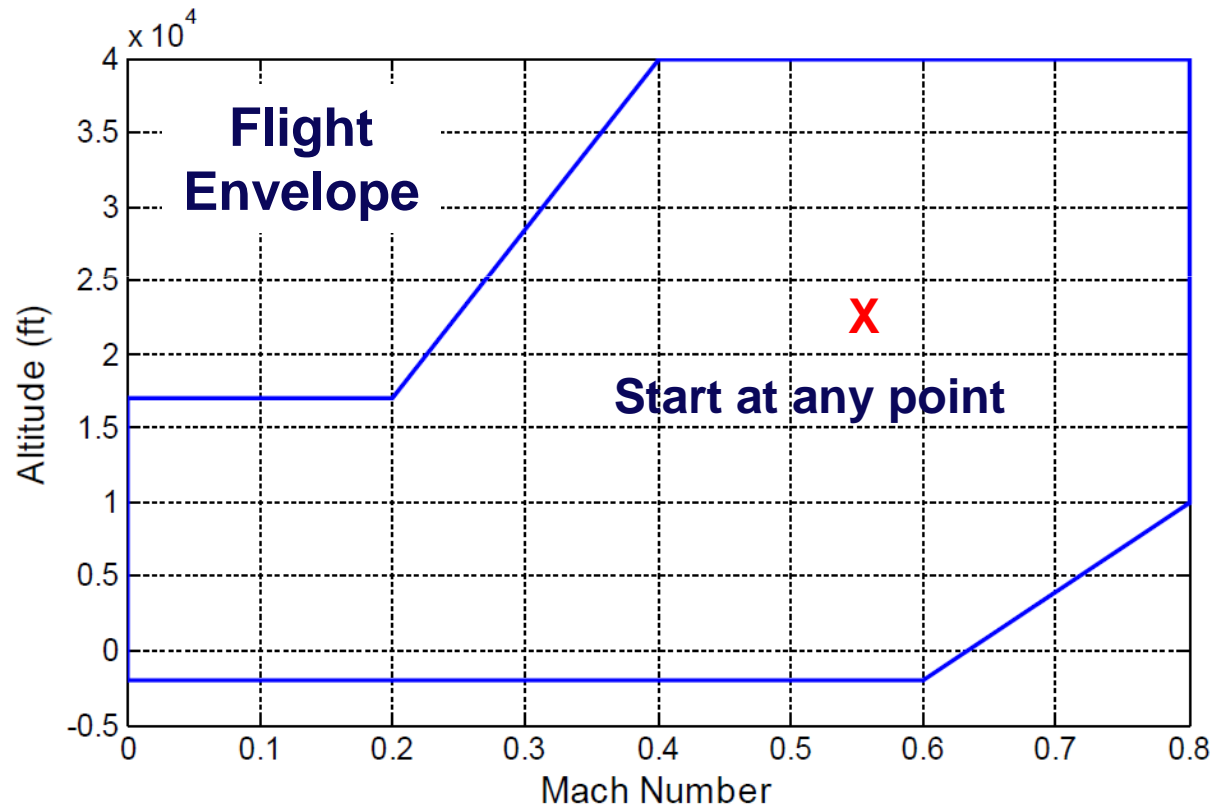
22 %=====
23 % Environmental Inputs
24 %=====
25 try
26     var_names = {'t_vec','alt','MN','dTamb','PLA'};
27     for i=1:length(var_names)
28         eval([var_names(i) ' = in_' var_names(i) ';'])
29     end
30 catch
31     t_vec = [0 15 15.1 30];
32     alt = 971; %altitude (0 to 40,000 ft)
33     MN = 0.2; %Mach Number (0 to 0.8)
34     dTamb = 0; %Delta Temperature (-30 to +50)
35     PLA = [55 55 75 75]; %PLA or Power Code (40 to 80.5)
36 end
37
38 %=====
39 % Operational Inputs
40 %=====
41 try
42     var_names = {'pwrTakeoff','custBleed'};
43     for i=1:length(var_names)
44         eval([var_names(i) ' = in_' var_names(i) ';'])
45     end
46 catch
47     pwrTakeoff = 0; % power takeoff (Hp)
48     custBleed = 0.0; % customer bleed (lb/s)
49 end
50
51 %=====
52 % Controller Inputs
53 %=====

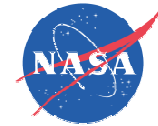
```



User Features: Steady-State Solver

- Steady-state engine model calculates the initial conditions for any point in flight envelope before simulation run
- Faster and more elegant than “flying” to desired starting point from a known initial flight condition





User Features: Linear Models

$$\dot{x} = Ax + Bu + Lh$$
$$y = Cx + Du + Mh$$

- Generate linear models about any equilibrium point (i.e., flight condition)
- Specify flight/health condition
- Specify state/input variable vectors
- Verify and save linear model

C-MAPSS40k Interface

File About

C-MAPSS40k Graphical Interface

Closed-Loop Linearize

Environmental Conditions

Altitude: 4000

Mach Number: 0.1

dTamb: 0

PLA: 68.5

Operational State

Power Takeoff: 0 HP

Customer Bleed: 0 psi

Engine Health Parameters

Engine Det: 0.0

Fan Eff: 0.0

Fan Flow: 0.0

Fan PR: 0.0

LPC Eff: 0.0

LPC Flow: 0.0

LPC PR: 0.0

HPC Eff: 0.0

HPC Flow: 0.0

HPC PR: 0.0

HPT Eff: 0.0

HPT Flow: 0.0

LPT Eff: 0.0

LPT Flow: 0.0

State Vector (x): [Nf ; Nc]

Control Inputs (u): Wf

Input Perturbation Size

Nf: 30.0

Nc: 30.0

Fan Eff: 1e-3

Fan Flow: 1e-3

Fan PR: 1e-3

LPC Eff: 1e-3

LPC Flow: 1e-3

LPC PR: 1e-3

HPC Eff: 1e-3

HPC Flow: 1e-3

HPC PR: 1e-3

HPT Eff: 1e-3

HPT Flow: 1e-3

LPT Eff: 1e-3

LPT Flow: 1e-3

Wf: 0.017

Verification Parameters

Change in PLA: 2 deg

PLA transient duration: 3 sec

Linearize

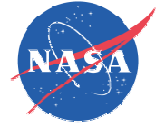
Verify System

Save System



Updates & Ongoing Work

- Heat soakage
 - Metal temperature state variables to enhance realism of transient performance
- Simulink library structure
 - Main Simulink file links to libraries for engine, controller, and actuators
- Different fuel types
 - Easily swappable thermodynamic tables
- Off-nominal variable stator vane positions
- High angle-of-attack
 - Inlet distortion effects due to high angle-of-attack flight



Summary

- Simulation of 40,000-lb_f class, high-bypass, dual-spool turbofan engine
- Physics-based, component-level model
- Faster than real-time
- Realistic control system
- Graphical/command-line user interfaces
- Linear model generation



Related NASA Publications

- Csank, Jeffrey, May, Ryan D., Litt, Jonathan S., and Guo, Ten-Huei, "Control Design for a Generic Commercial Aircraft Engine," AIAA-2010-6629, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, July 25-28, 2010, also NASA/TM—2010-216811, October 2010.
- May, Ryan D., Csank, Jeffrey, Lavelle, T. M., Litt, Jonathan S., and Guo, Ten-Huei, "A High-Fidelity Simulation of a Generic Commercial Aircraft Engine and Controller," AIAA-2010-6630, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Nashville, TN, July 25-28, 2010, also NASA/TM—2010-216810, October 2010.

Available for download from the NASA Software Repository

<https://sr.grc.nasa.gov/public/project/77/>